

UNCLASSIFIED

AD 297 397

*Reproduced
by the*

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

23-2-5
NRL Report 5879

CATALOGED BY ASTIA
AD NO. 297397

297 397

Three-Phase Static Inverter with Waveform Synthesis

D. J. HANRAHAN AND W. K. GARDNER

*Energy Conversion Branch
Electronics Division*

January 21, 1963

ASTIA

MAR 4 1963



U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

Three-Phase Static Inverter with Waveform Synthesis

D. J. HANRAHAN AND W. K. GARDNER
*Energy Conversion Branch
Electronics Division*

The principle of a new, three-phase, static inverter is demonstrated by means of a model circuit. Static inverters are replacing rotary inverters for dc to ac conversion in aircraft, missile, and satellite electrical power systems. Where sinusoidal output is required, there is a design conflict between efficiency and waveform. The new circuit retains the efficiency of switching, but switched portions of the input are combined so as to approximate a sinusoidal output, thereby minimizing filter requirements. Controlled rectifiers are used because they are available in higher power ratings than transistors. The evolution of the new circuit from the basic parallel inverter circuit is traced.

A multiwinding transformer (suggested by Toffolo of NRL) is used to obtain a three-step approximation to a sine wave. Primary turns in the ratio $\sqrt{3}:3 + \sqrt{3}:3 + 2\sqrt{3}$ theoretically eliminate all harmonics up to the eleventh. The model circuit, constructed with turns in the ratio 1:3:4, exhibits even better waveform because of the filtering effect of the commutating capacitors. A simple criterion for successful commutation is established: the dc bus voltage must be greater than zero when each gate signal is applied.

The main advantage of the new circuit is the reduction of filtering necessary for acceptable waveform. The principle may be employed with more switching elements to obtain even better waveform, but the increased complexity is not considered worth the gain. Another advantage of the circuit is that it is inherently a three-phase circuit, rather than three single-phase circuits, which promises construction economies and better performance under unbalanced load.

INTRODUCTION

Static inverters are dc to ac converters without moving parts. They are under development as replacements for rotary inverters in aircraft and missile electrical systems. They should, therefore, be reliable and efficient with a minimum of weight and volume. Also, inverters are finding increased application because of the dc nature of most direct-conversion power sources.

Static converter circuits employing vacuum or gas tubes have been known for many years, but tubes are not sufficiently reliable for airborne or space use. The advent of semiconductor devices has opened this critical field to application of both the old and newer static circuits. The most efficient operation of these devices occurs in the switching mode, and herein lies the major design problem of the static inverter: switching tends to generate a square wave, which is ideal for dc to dc conversion, but ac output is usually required to be sinusoidal. Retention of switching then requires output filtering which leads to excessive weight and size, especially for large power ratings. This report presents a new circuit which employs switching to obtain a step approximation to a sine wave, thereby minimizing the filtering necessary to meet a specified harmonic content.

THE PARALLEL INVERTER

Controlled rectifier (CR) circuits are of more interest than those using transistors because CR's are available in higher power ratings. The best known CR circuit is the parallel inverter (1) shown in Fig. 1. Presently available CR's are characterized by an inability to be turned off, except by circuit action. That is the purpose of the choke and commutating capacitor in Fig 1. These elements also influence the output waveform. The CR gates are pulsed alternately every 180 degrees, establishing the output frequency.

A three-phase inverter may be obtained by simply using three channels of the type shown in Fig. 1. Gate signals are properly phased, and each

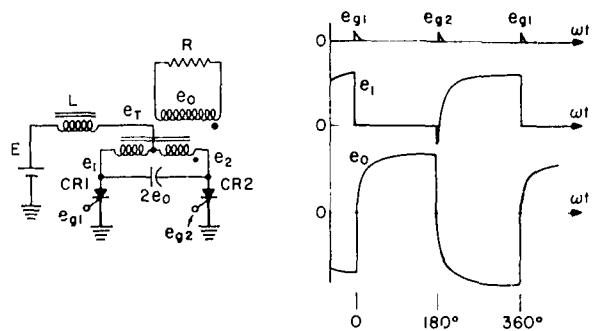


Fig. 1 Single-phase, parallel inverter
(180° switching)

CR conducts for 180 degrees. Hudson (2) has shown, however, that a better circuit is obtained by the arrangement shown in Fig. 2, wherein each CR conducts for 60 degrees. This requires only one choke, gives a better waveform, and increases the capacity of individual rectifiers by some 17 percent because of the reduced duty cycle.

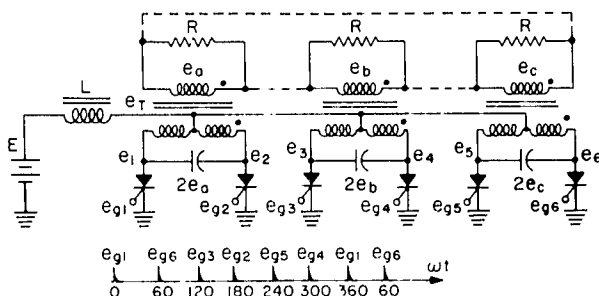


Fig. 2 - Three-phase, parallel inverter (60° switching) after Hudson (Ref. 2)

WAVEFORM SYNTHESIS

The principle upon which the new circuit of this report is based is that of a multiwinding transformer proposed by Toffolo (3) to improve the waveform of currents taken by a three-phase transformer-rectifier. He used a synthetic secondary so that all three phases of the transformer output were fed by each phase of the input. Having the inverse problem, we used a synthetic primary so that each primary winding fed all three phases of the secondary at the same time.

Figure 3 shows the circuit of Fig. 2 redrawn in order to consider application of the synthetic primary. Magnetic coupling is vertical and the firing order is 1,2,3,4,5,6. One might think that providing additional primary windings, so that there is a string of three connected to each CR with turns in the ratio 1:1:2, would achieve a two-step approximation to a sine wave. This is so, but the two-step approximation is already inherent in the circuit of Fig. 2 by virtue of the three-phase connection, one form of which is shown dotted. Even if three isolated single-phase loads were to be supplied, the three-phase connection (or synthetic primary) would be necessary for commutation. Using the synthesis principle to advantage requires additional switching elements.

Figure 4 shows the power portion of the circuit developed for a three-step approximation to a sine wave. Each CR conducts for 30 degrees. Gate pulses are obtained from a Marzolf ring generator (4), though any suitable circuit may be used (5).

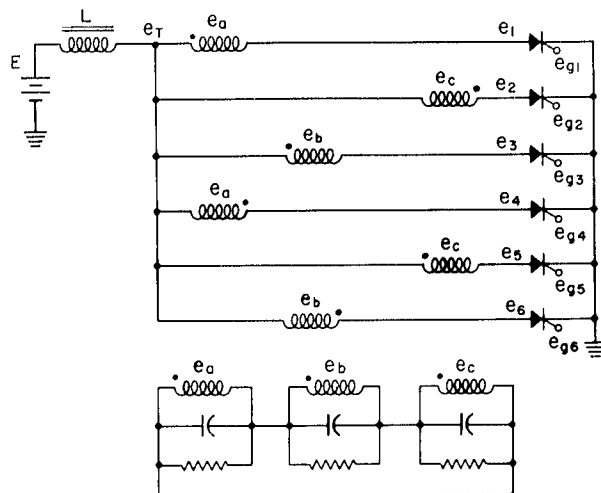


Fig. 3 - Hudson inverter of Fig. 2 redrawn (firing order 1,2,3,4,5,6)

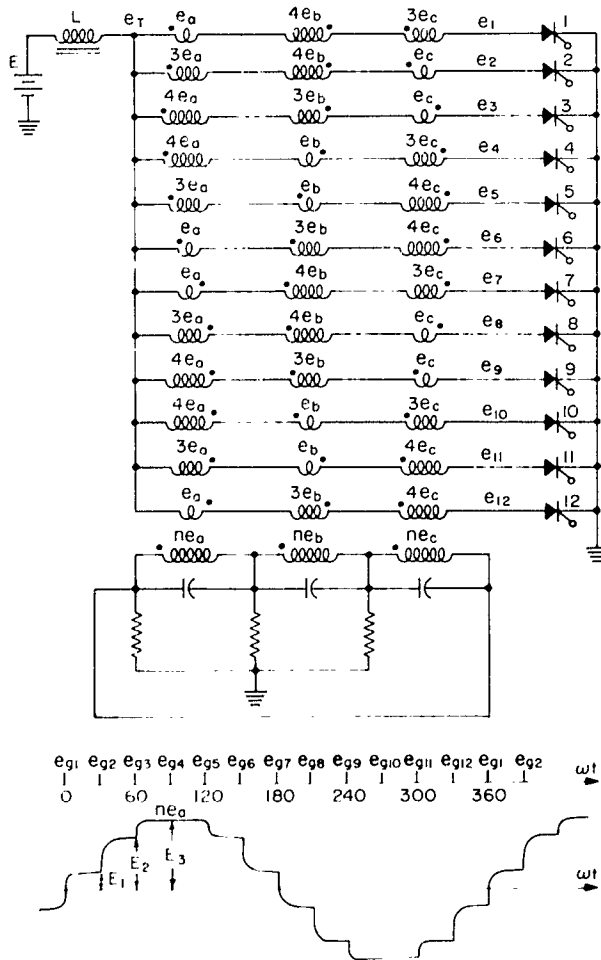


Fig. 4 - Parallel inverter with 30° switching and a three-step approximation to a sine wave

The primary-turns ratio is chosen so that

$$e_a + e_b + e_c = 0.$$

Thus, these voltages contain no multiples of the third harmonic. Also, symmetry precludes even harmonics. As shown in Appendix A for a three-step wave, if the primary-turns ratio is also chosen to "pitch out" the 5th harmonic, the 7th is eliminated too. The next harmonic to occur is the 11th and it is 9 percent of the fundamental. The required ratio is

$$\sqrt{3}:3 + \sqrt{3}:3 + 2\sqrt{3}.$$

For convenience the model circuit was constructed with a primary-turns ratio of 1:3:4. The actual waveform is much better than that predicted by Appendix A, and sketched in Fig. 4, mainly because of the filtering effect of the commutating capacitors. Oscillograms of a model circuit output are shown in Fig. 5.

A discussion of commutation in this circuit is given in Appendix B. It is concluded that circuit parameters must be such as to insure two conditions: that (a) gate pulses arrive before the circuit reaches a steady-state condition, and (b) the dc bus voltage (e_r) be positive at the instant of gating. In brief, $e_r > 0$.

CONCLUSIONS

A great improvement in waveform has been demonstrated by the three-phase, parallel inverter with 30-degree switching and wave synthesis. Twice as many switching elements are required as for the basic inverter circuit, but this is justified by the reduction in filter size and efficiency loss. Further improvement in waveform may be obtained by even more switching elements, but the gain is not believed worth the increased complexity.

Since the development of this circuit, we have learned of others (6,7,8) employing the synthesis principle in different ways, some also using "the first harmonic the eleventh" ratio reported here. A more general mathematical treatment was given recently by Corey (9). The principle is sound and may be utilized in many different circuits. The circuit presented here is worth considering. It uses CR's rather than transistors, with the required commutating capacitors enhancing the waveform, and is a three-phase circuit rather than three single-phase circuits.

RECOMMENDATIONS

The circuit presented should be developed further to determine its position with respect to other synthesis schemes. Investigations should be made of its potential for material economies, unbalance capability, and protection and control requirements.

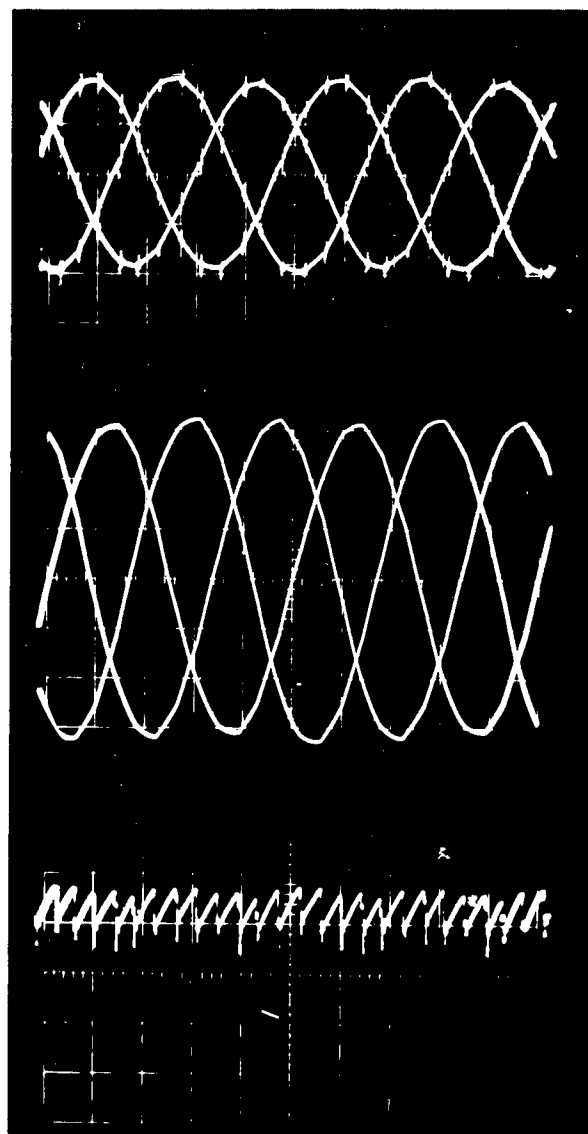


Fig. 5 Oscillograms of the output from a model circuit based on the circuit shown in Fig. 4. Top: phase voltages; middle: line voltages; bottom: dc bus voltage e_r . The horizontal, graduated grid line is zero.

REFERENCES

1. General Electric Rectifier Components Department, "Silicon Controlled Rectifier Manual," Auburn, N.Y., 2nd ed., 1961
2. Hudson, C.S., "Notes on the Design of Static Inverters," RAE Tech. Note EL 185, Sept. 1960, Great Britain Royal Aircraft Establishment, Ministry of Aviation, London, W.C. 2
3. Toffolo, D.S., "Regulated Linear Transformer-Rectifier Power Supplies," NRL Report 5494, July 1960
4. Marzolf, J.M., "Transistorized Ring-Type Pulse Generator," NRL Report 5640, July 1961
5. Marshall, D.E., "A Six-Element Ring Counter Circuit for Phase Locking a Three-Phase Static Inverter," RAE Tech. Note EL 192, Jan. 1961, Great Britain Royal Aircraft Establishment, Ministry of Aviation, London, W. C. 2
6. Kernick, A., Roof, J.L., and Heinrich, T.M., "Static Inverter with Neutralization of Harmonics," AIEE Conference Paper 61-891, Aero-Space Transportation Conference, June 26, 1961
7. Salters, G., "A High Power D.C.-A.C. Inverter with Sinusoidal Output," Electronic Eng. 33: 586-591, Sept. 1961
8. Anderson, D.L., Willie, A.E., and Winkler, C.E., "Static Power Inverter Utilizing Digital Techniques and Harmonic Cancellation," AIEE Conference Paper 62-1148, Summer General Meeting, June 17, 1962
9. Corey, P.D., "Methods for Optimizing the Waveform of Stepped-Wave Static Inverters," AIEE Conference Paper 62-1147, Summer General Meeting, June 17, 1962

APPENDIX A FOURIER ANALYSIS OF THREE-STEP WAVE

Let $y = f(x)$ represent the three-step wave shown in Fig. 4, except that we imagine the steps to be square. Such would be the case for open-circuit secondaries and perfect switching. (Primary circuit resistance is already neglected.) Expressing y as a Fourier series and using symmetry

$$y = \sum_{n=1}^{\infty} A_n \sin nx, \quad n \text{ odd}, \quad (\text{A1})$$

where

$$A_n = \frac{2}{\pi} \int_0^{\pi} y \sin nx \, dx. \quad (\text{A2})$$

Evaluating A_n for the fundamental in terms of the steps E_1, E_2 , and E_3 ,

$$A_1 = \frac{2}{\pi} \left[(2 - \sqrt{3}) E_1 + (\sqrt{3} - 1) E_2 + E_3 \right]. \quad (\text{A3})$$

Since

$$E_1 + E_2 = E_3 \quad (\text{A4})$$

then

$$A_1 = \frac{2}{\pi} \left[(3 - \sqrt{3}) E_3 + (2\sqrt{3} - 3) E_2 \right]. \quad (\text{A5})$$

Since the third harmonic is absent, the next harmonic is the fifth. Thus

$$A_5 = \frac{2}{5\pi} \left[(3 + \sqrt{3}) E_3 - (3 + 2\sqrt{3}) E_2 \right]. \quad (\text{A6})$$

This will vanish for

$$\frac{E_2}{E_3} = \frac{3 + \sqrt{3}}{3 + 2\sqrt{3}}. \quad (\text{A7})$$

Also

$$A_7 = \frac{2}{7\pi} \left[(3 + \sqrt{3}) E_3 - (3 + 2\sqrt{3}) E_2 \right] = \frac{5}{7} A_5. \quad (\text{A8})$$

Substituting Eq. (A7) in Eq. (A8) causes A_7 to vanish.

The next harmonic is the 11th given by

$$A_{11} = \frac{2}{11\pi} (3 - \sqrt{3}) E_3 + (2\sqrt{3} - 3) E_2, \quad (\text{A9})$$

from which, using Eq. (A7),

$$\frac{A_{11}}{A_1} = \frac{12}{11(2 + \sqrt{3})\pi} = 0.093. \quad (\text{A10})$$

APPENDIX B COMMUTATION

Commutation of the circuit in Fig. 4 may be explained by considering the transfer of current from CR1 to CR2 as an example.

$$e_T = e_a - 4e_b + 3e_c + e_1 \quad (\text{B1})$$

and

$$e_T = 3e_a - 4e_b + e_c + e_2, \quad (\text{B2})$$

so

$$2e_c + e_1 = 2e_a + e_2. \quad (\text{B3})$$

Neglecting the forward drop when CR1 is conducting,

$$e_2 = 2(e_c - e_a). \quad (\text{B4})$$

But e_T is distributed so that

$$e_a = \frac{1}{26} e_T \text{ and } e_c = \frac{3}{26} e_T. \quad (\text{B5})$$

Therefore

$$e_2 = \frac{2}{13} e_T, \quad (\text{B6})$$

and CR2 will conduct when fired if $e_T > 0$. This can be insured by elimination of the choke, but we shall see that the choke is necessary.

If CR2 does conduct, e_2 is zero and the voltages across the capacitors cannot change instantly. Even neglecting primary resistance, discharge is blocked by the CR's. Consequently e_1 must suddenly change according to Eq. (B3). Since Eq. (B1) still applies, e_T suffers a corresponding change. That is the reason for the choke; without it, $e_T = E$. Equation (B3) gives

$$e_1 = 2(e_a - e_c) = -\frac{2}{13} e_T. \quad (\text{B7})$$

The positive e_T which permitted CR2 to conduct when fired also insures the turn off of CR1, and the transfer of current is accomplished.

There are, then, two requirements for successful commutation: (a) Due to actual primary resistance, e_T goes to zero in the steady state. The signal to fire CR2 must come before this state is reached, and (b) the voltage e_T must vary in such a way as to be positive when CR2 is fired. Both requirements may be expressed by $e_T > 0$ at the instant of firing. The variation of e_T for the circuit constructed is shown in Fig. 5.

* * *

UNCLASSIFIED

U.S. Naval Research Laboratory, Report 5879.
THREE-PHASE STATIC INVERTER WITH WAVEFORM
SYNTHESIS, by D. J. Hanrahan and W. K. Gardner. 5 pp. &
figs., January 21, 1963.

The principle of a new, three-phase, static inverter is demonstrated by means of a model circuit. Static inverters are replacing rotary inverters for dc to ac conversion in aircraft, missile, and satellite electrical power systems. Where sinusoidal output is required, there is a design conflict between efficiency and waveform. The new circuit retains the efficiency of switching, but switched portions of the input are combined so as to approximate a sinusoidal output, thereby minimizing filter requirements. Controlled rectifiers are used because they are available in higher power ratings than transistors. The evolution of the new circuit from the basic parallel inverter circuit is traced.

A multivinding transformer (suggested by Toffolo of NRL) is used to obtain a three-step approximation to a sine wave. Primary turns in the ratio $\sqrt{3} : 1 : \sqrt{3} : 1 - 2\sqrt{3}$ theoretically eliminate all harmonics up to the eleventh. The model circuit, constructed with turns in the ratio 1:3:4, exhibits even better waveform

(Over)

UNCLASSIFIED

UNCLASSIFIED

U.S. Naval Research Laboratory, Report 5879.
THREE-PHASE STATIC INVERTER WITH WAVEFORM
SYNTHESIS, by D. J. Hanrahan and W. K. Gardner. 5 pp. &
figs., January 21, 1963.

The principle of a new, three-phase, static inverter is demonstrated by means of a model circuit. Static inverters are replacing rotary inverters for dc to ac conversion in aircraft, missile, and satellite electrical power systems. Where sinusoidal output is required, there is a design conflict between efficiency and waveform. The new circuit retains the efficiency of switching, but switched portions of the input are combined so as to approximate a sinusoidal output, thereby minimizing filter requirements. Controlled rectifiers are used because they are available in higher power ratings than transistors. The evolution of the new circuit from the basic parallel inverter circuit is traced.

A multivinding transformer (suggested by Toffolo of NRL) is used to obtain a three-step approximation to a sine wave. Primary turns in the ratio $\sqrt{3} : 1 : \sqrt{3} : 1 - 2\sqrt{3}$ theoretically eliminate all harmonics up to the eleventh. The model circuit, constructed with turns in the ratio 1:3:4, exhibits even better waveform

(Over)

UNCLASSIFIED

- I. Static inverters - Circuits
2. Static inverters - Anal.

- I. Hanrahan, D. J.
- II. Gardner, W. K.

UNCLASSIFIED

1. Static inverters - Circuits
 2. Static inverters - Anal.
- I. Hanrahan, D. J.
 - II. Gardner, W. K.

U.S. Naval Research Laboratory, Report 5879.
THREE-PHASE STATIC INVERTER WITH WAVEFORM
SYNTHESIS, by D. J. Hanrahan and W. K. Gardner. 5 pp. &
figs., January 21, 1963.

The principle of a new, three-phase, static inverter is demonstrated by means of a model circuit. Static inverters are replacing rotary inverters for dc to ac conversion in aircraft, missile, and satellite electrical power systems. Where sinusoidal output is required, there is a design conflict between efficiency and waveform. The new circuit retains the efficiency of switching, but switched portions of the input are combined so as to approximate a sinusoidal output, thereby minimizing filter requirements. Controlled rectifiers are used because they are available in higher power ratings than transistors. The evolution of the new circuit from the basic parallel inverter circuit is traced.

A multivinding transformer (suggested by Toffolo of NRL) is used to obtain a three-step approximation to a sine wave. Primary turns in the ratio $\sqrt{3} : 1 : \sqrt{3} : 1 - 2\sqrt{3}$ theoretically eliminate all harmonics up to the eleventh. The model circuit, constructed with turns in the ratio 1:3:4, exhibits even better waveform

(Over)

UNCLASSIFIED

UNCLASSIFIED

1. Static inverters - Circuits
 2. Static inverters - Anal.
- I. Hanrahan, D. J.
 - II. Gardner, W. K.

U.S. Naval Research Laboratory, Report 5879.
THREE-PHASE STATIC INVERTER WITH WAVEFORM
SYNTHESIS, by D. J. Hanrahan and W. K. Gardner. 5 pp. &
figs., January 21, 1963.

The principle of a new, three-phase, static inverter is demonstrated by means of a model circuit. Static inverters are replacing rotary inverters for dc to ac conversion in aircraft, missile, and satellite electrical power systems. Where sinusoidal output is required, there is a design conflict between efficiency and waveform. The new circuit retains the efficiency of switching, but switched portions of the input are combined so as to approximate a sinusoidal output, thereby minimizing filter requirements. Controlled rectifiers are used because they are available in higher power ratings than transistors. The evolution of the new circuit from the basic parallel inverter circuit is traced.

A multivinding transformer (suggested by Toffolo of NRL) is used to obtain a three-step approximation to a sine wave. Primary turns in the ratio $\sqrt{3} : 1 : \sqrt{3} : 1 - 2\sqrt{3}$ theoretically eliminate all harmonics up to the eleventh. The model circuit, constructed with turns in the ratio 1:3:4, exhibits even better waveform

(Over)

UNCLASSIFIED

UNCLASSIFIED

because of the filtering effect of the commutating capacitors. A simple criterion for successful commutation is established: the dc bus voltage must be greater than zero when each gate signal is applied.

The main advantage of the new circuit is the reduction of filtering necessary for acceptable waveform. The principle may be employed with more switching elements to obtain even better waveform, but the increased complexity is not considered worth the gain. Another advantage of the circuit is that it is inherently a three-phase circuit, rather than three single-phase circuits, which promises construction economies and better performance under unbalanced load.

UNCLASSIFIED

UNCLASSIFIED

because of the filtering effect of the commutating capacitors. A simple criterion for successful commutation is established: the dc bus voltage must be greater than zero when each gate signal is applied.

The main advantage of the new circuit is the reduction of filtering necessary for acceptable waveform. The principle may be employed with more switching elements to obtain even better waveform, but the increased complexity is not considered worth the gain. Another advantage of the circuit is that it is inherently a three-phase circuit, rather than three single-phase circuits, which promises construction economies and better performance under unbalanced load.

UNCLASSIFIED

UNCLASSIFIED

because of the filtering effect of the commutating capacitors. A simple criterion for successful commutation is established: the dc bus voltage must be greater than zero when each gate signal is applied.

The main advantage of the new circuit is the reduction of filtering necessary for acceptable waveform. The principle may be employed with more switching elements to obtain even better waveform, but the increased complexity is not considered worth the gain. Another advantage of the circuit is that it is inherently a three-phase circuit, rather than three single-phase circuits, which promises construction economies and better performance under unbalanced load.

UNCLASSIFIED

UNCLASSIFIED

because of the filtering effect of the commutating capacitors. A simple criterion for successful commutation is established: the dc bus voltage must be greater than zero when each gate signal is applied.

The main advantage of the new circuit is the reduction of filtering necessary for acceptable waveform. The principle may be employed with more switching elements to obtain even better waveform, but the increased complexity is not considered worth the gain. Another advantage of the circuit is that it is inherently a three-phase circuit, rather than three single-phase circuits, which promises construction economies and better performance under unbalanced load.

UNCLASSIFIED

DISCLAIMER NOTICE

**THIS DOCUMENT IS BEST QUALITY
PRACTICABLE. THE COPY FURNISHED
TO DTIC CONTAINED A SIGNIFICANT
NUMBER OF PAGES WHICH DO NOT
REPRODUCE LEGIBLY.**

/